A SIMPLIFIED, CW, RANDOM-NOISE RADAR SYSTEM

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THESIS

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ABSTRACT

Experiments with a CW, random-noise, X-band, radar ranging system are presented, following the technique proposed and used by G. L. Poirier. The correlation signal-processing method differs from that of other noise radars in that no delay lines are required. The signal-processing technique also decorrelates clutter and other interference, including the transmitted signals of other radar systems identical except for their statistically independent noise sources. An application to small-vessel navigation systems is proposed. Other applications in communications and jamming systems are considered. The experiments verify a ranging accuracy of 1.45 meters at a range of 154 meters. The range capability extends from a minimum of 30 meters to the radar horizon at 19,000 meters in the system constructed. The minimum range and accuracy capabilities exceed those of existing pulsed radars installed in small craft. Possible solid-state implementations using currently available devices are outlined. Proposals for future experiments are made, including shortening of minimum range by increasing transmitted bandwidth, and increasing accuracy by refinement of the laboratory model.

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I. INTRODUCTION

There is a need in mine and amphibious warfare for the smaller afloat units to have precise, short-range navigation systems. The operation of these systems should be independent of shore-station assistance. The minecraft need the accuracy for mine laying and sweeping, the amphibious craft for timing and control [1]. A passive system would be desirable for protection of the navigating unit from ECM intercept. The navigation system should be useable in all visibility conditions.

Existing systems are of insufficient accuracy, and depend on good visibility. One minesweeper system, for example, uses radar ranges (accuracy $\pm$ 10 yards) and visual bearings to reference buoys or other markers [2]. The resulting positions, required every 30 seconds, have an expected error of 50 yards (standard deviation). The error includes the reference-buoy position error of up to 10 yards. The system depends on good visibility, and its effective range is from a minimum of about 200 yards to the visual horizon from the pilothouse level. The normal pulsed radar used for ranging is easily detected by ECM intercept, and may interfere with other similar radar systems.

A VHF phase-comparison navigation system has been proposed by Thomas [1] and MacKenzie [3]. This system has a dependable range of 40 miles with a predicted accuracy of $\pm$ 20 meters or less for periods of up to four hours from start of use of the system. The system is independent of visibility conditions, and is passive for the navigating unit. Stable master and slave oscillators are required in this system.

The radar system proposed in this thesis should have an application in the minesweeper navigation system mentioned above. The technique was originally proposed by Poirier [4]. The accuracy of the proposed radar system should result in a range error of 1.5 meters, under ideal conditions, to the radar horizon. This range error is less than existing pulsed radars for small craft. The ideal conditions include a perfectly stabilized platform and large, discrete radar targets. The accuracy in ranging will eliminate dependence on visual bearings, if at least three reference targets are available. The radar uses low-power, CW, band-limited random noise at nine GHz as a transmitted signal. The receiver differs from other random noise radars in that analysis is continuous and on a frequency basis. No delay lines are required. The system is active, but the low power and random nature of the transmitted signal provide some security from ECM intercept. The statistical independence of individual noise sources would allow many units using the same equipment to operate in close proximity without mutual interference. When fully implemented with solid-state devices, followed by double spectrum analysis, the resulting "A" scope presentation would require little operator attention to determine range. The solid-state implementation would also result in a system with a weight on the mast of about 20 pounds, or one-third that of the smallest pulsed radars currently installed in small craft [8].

The minimum range capability is better than the normal pulsed radar, and could be used for station-keeping in formation and for approaches to within 30 yards of larger ships at sea. The minimum range capability improves as the transmitted bandwidth is increased. Cooper and Gassner [9] indicate that bandwidths of at least 100 MHz are attainable in

available components. This bandwidth would result in a minimum range of three meters.

The basic ranging system could easily be modified for use in range-rate determination, bearing measurements, jamming, or voice communications.

II. THEORY AND SYSTEM CONCEPT

The typical radar obtains range information from time-delay analysis, together with signal processing of the signal envelope (or correlation-function envelope). Two exceptions to this are the multifrequency CW radar [10] and the simplified noise radar being investigated here. In Reference 4, it is explained that under certain coherency and relative bandwidth conditions, the power spectrum of the reflections of quasimonochromatic radiation from scatterers (targets) is cosine-modulated. Analysis of this modulation can yield information on the range and magnitude of the target(s). The modulation frequencies depend only on the time delay, τ. The argument of the cosine modulation is $\frac{\omega\tau}{2}$, where ω is the angular frequency of the modulation. Bartling [5] shows a similar result, and further states that the cosine modulation can be looked upon as a phase effect resulting from the interference of two signals, one of which is delayed. Bartling also shows that equivalent information about target range may be determined from either a correlation technique or by a detector followed by Fourier analysis. Schindler [6] has done additional theoretical work on optimizing the receiver system when some target parameters are known in advance. Rotman [7] has done a theoretical analysis of the statistics of scattered, quasimonochromatic radiation.

The equations developed by Poirier [4], and used in this paper are presented in Appendix A. Some other useful equations are listed below.

The maximum range as given by the radar equation [10] is

$$R'_{max} = \left(\frac{P_t G^2 \lambda^2 \sigma_T}{(4\pi)^3 k T_o B_N F_N \frac{S_o}{N_o}} \right)^{1/4} \tag{1}$$

where P_t = transmitted power, watts

G = gain of transmitting antenna = gain of receiving antenna

λ = mean wavelength radiated, meters

σ_T = target cross section, square meters

k = Boltzmann's constant = 1.38×10^{-23} joules/Hz

T_o = standard temperature = 290 deg K

B_n = receiver noise bandwidth

F_n = noise figure of the receiver

$\frac{S_o}{N_o}$ = minimum receiver output signal-to-noise ratio required for the desired probability of detection.

The maximum range as determined by the radar horizon limitation [11] is

$$R''_{max} = .869\left[\sqrt{2h_1} + \sqrt{2h_2}\right] \quad \text{(nautical miles)} \tag{2}$$

where h_1 = radar antenna height, feet

h_2 = target height, feet

An error analysis on equations A-(4) and A-(6) results in

$$\delta R = \pm R \left| \frac{\Delta(\Delta f_m)}{\Delta f_m} \right| \tag{3}$$

where δR = range error after one spectrum analysis

Δf_m = frequency difference between nulls

$\Delta(\Delta f_m)$ = error in measurement of Δf_m

The error in measurement is estimated as the scale accuracy of the first spectrum analyzer divided by the number of nulls displayed.

An error equation valid when two spectrum analyses are performed is obtained from Equations A-(5) and A-(6) as

(4)
$$\delta R' = \pm R\left[\left|\frac{\Delta f_m'}{f_m'}\right| + \left|\frac{\Delta S_s}{S_s}\right|\right]$$

where $\delta R'$ = range error after two spectrum analyses

f_m' = frequency measured on the second spectrum analyzer

$\Delta f_m'$ = error in measurement of frequency on the second spectrum analyzer

S_s = sweep speed of the first spectrum analyzer, Hz/sec

ΔS_s = error in determining S_s.

The doppler-induced frequency shift is given by [10] as

(5)
$$f_d = \frac{102\, v_r}{\lambda}$$

where v_r = relative speed between radar and target (knots)

λ = radiated wavelength, cm.

The radar system may be implemented in several ways, one of which is shown in Figure 1. The microwave noise source is injected into a bandpass filter. The output of the filter goes into travelling-wave-tube amplification and then to the transmitting antenna. The signal from the receiving antenna is added together with an attenuated sample

of the transmitted signal in a microwave "T". After amplification by a TWT amplifier, the summed signal is led to the input of a microwave spectrum analyzer. This spectrum analyzer can be used to determine range in accordance with Equation A-(4). The video signal of the first spectrum analyzer is used as an input to a video spectrum analyzer. The display of this spectrum analyzer is an "A" scope presentation from which range can be determined by use of Equation A-(5).

The numerical values shown in Figure 1 are the nominal values used for the laboratory model to be discussed later. The values satisfy the coherence and relative bandwidth conditions stated by Poirier [4]. The conditions are that the range to the target be much greater than the coherence length of the radiation (Equation A-8), and that the transmitted bandwidth be much less than the mean frequency transmitted.

The following table (Table 1) is a summary of the range characteristics resulting from use of the nominal system values of Figure 1, in the equations previously developed.

Range	meters
To radar horizon	19,200
Maximum, by radar equation	15,480
Maximum, by bandwidth limitation	15,000
Predicted accuracy at 1500 meters	± 1.28
Predicted accuracy at 150 meters	± 0.3
Resolution (estimated)	12.0
Minimum	30.0

Table 1. Radar System Range Characteristics for Antenna Height = 30 feet and Target Height = 5 feet.

A non-stationary target will produce modulations at the doppler frequency. The additional modulations will not interfere with the application proposed in the Introduction. For example, a 100-knot target, inside the maximum range, would produce a frequency shift of approximately 6800 Hz (Equation (5)). After signal processing this target would show falsely to be at a range of 44,000 meters which is well outside the maximum range possible in the system.

III. LABORATORY WORK

The laboratory model was formed from standard microwave test equipment and from components available from existing radar systems in the radar laboratory. The resulting noise generation method was primitive, but was sufficient for the experiments conducted. The laboratory model was not portable, thus forcing operation in an environment of many trees and buildings. In this environment, few suitable targets were available. The superstructure of one of the buildings offered the one large, discrete target for most of the experiments. The range to this target, as determined by measuring tape, is 153.45 $\pm$ .2 meters.

A block diagram of the laboratory system is shown in Figure 2. Photographs of the transmitter and receiver are in Figures 3 and 4. In the transmitter, the "noise source" consists of two balanced mixers operating in conjunction with an IF amplifier and an X-band local oscillator. The noise is generated primarily in the first mixing diodes. The IF amplifier receives the down-converted output of the first mixer, and amplifies this output at 60 MHz with a bandwidth of about 12 MHz. The second mixer is fed by this amplified

output and the local oscillator. The output of this mixer is an up-converted X-band noise signal. The bandpass filter restricts the noise signal to a 10-MHz bandwidth. The filter also provides a suitable load for the previous stages. The output of the bandpass filter is amplified by two stages of TWT amplification. The first stage is a Hewlett Packard 494A, and the second is a Litton 3998-50. A Hewlett Packard 431A Power Meter monitors the output through a directional coupler. The reference signal for the receiver is led off through another directional coupler through a variable attenuator to a microwave "T" at the receiver input. The transmitting antenna is a standard horn with a gain of about 30 db. The power output of one watt was obtained without using the full gains available in the IF amplifier and the TWT amplifiers.

The receiving antenna is a 24-inch diameter parabolic dish from an obsolete fire-control system. The antenna gain was estimated at 30 db. The isolators shown were necessary to eliminate spurious signals caused by multiple reflections in the RF portions of the system. The input for the receiver TWT amplifier (another Hewlett Packard 494A) is formed from the sum of the received signal and the attenuated sample of the transmitted signal. The output of the TWT is led to the input terminals of a Lavoie UPM-84 Spectrum Analyzer. The sensitivity of this spectrum analyzer was measured as -65 dbm. For good modulation characteristics in the display, it was not necessary to have equal power in the received and reference signals as reported by Poirier. The signals could differ by as much as 6 db. The one-KHz bandwidth was used. The video signal of the first spectrum analyzer is led to the video spectrum analyzer (Tektronix 1L5 Plug-in with a Tektronix 535 Oscilloscope), to give the "A" scope display.

The "A" scope display was demonstrated only qualitatively. A successful "A" scope would allow resolution of multiple targets. At the frequency of the primary target (f_m = 450 KHz), the display width of this video spectrum analyzer was sufficient only to provide a "range gate" of 30 meters. Furthermore, small errors in determining (setting) the sweep speed of the first spectrum analyzer resulted in large errors in range.

The transmitted, received and summed signal waveforms are shown in the spectrum analyzer photographs of Figures 5 and 6. It can be seen that the transmitted waveform has the shape characteristic of AM Gaussian noise for about two MHz of the transmitted bandwidth of 10 MHz. The overall shape of the transmitted signal is the same as the gain characteristics of the modified IF amplifier used. The standard deviation of the signal was estimated as four MHz. Standard deviations of noise waveforms can be accurately determined by use of a sampling oscilloscope and a pulse height analyzer [12]. In the summed signal displays of Figure 6, the modulation nulls can be seen clearly.

IV. RESULTS

The range to the primary target at 153.45 $\pm$ .2 meters by measuring tape was determined to be 154.4 $\pm$ .3 meters in thirty observations, yielding a worst-case accuracy of 1.45 meters.

The predicted minimum range of 30 meters was demonstrated by ranging on the trunk of a nearby redwood tree on a calm day.

The immunity of the ranging system to clutter-like interference was partially demonstrated by ranging to the same redwood tree on a windy day. The movement of the branches induced a superimposed, wave-like pattern on the spectrum analyzer display. The operator could

continue to determine the range by careful observation. The frequency nulls could still be seen clearly. Photographs at one-fifth second shutter speed, however, did not reproduce the same display as seen by the operator.

The maximum predicted range was partially demonstrated by momentarily ranging on small aircraft passing through the radiation field at ranges of about 10,000 meters. It was observed that modulated signal returns were being received.

V. PROPOSED SOLID-STATE IMPLEMENTATION

Recent advances in microwave integrated-circuit and hybrid-circuit techniques [13] indicate that solid-state implementation is practical. A prototype implementation with discrete components can be made with currently available devices [14]. Transmitted bandwidths of 10 MHz or greater can easily be achieved [14].

The antennas, transmitter, and receiver preamplifier could be located on the mast of a small craft (or instrumentation tower) following current practices for small-craft radars [8]. A coaxial cable would be sufficient for connection to the remainder of the receiver (spectrum analyzers) at a lower level.

The transmitter could be constructed using various forms of power oscillators driven by a "noise power supply" (DC-plus-noise). The power oscillator used could either be a klystron or a solid-state device [14]. An inexpensive klystron (with feedback to obtain oscillations) with a noise power supply on the cathode would produce suitable signal outputs from milliwatts to several watts. An arc discharge at the cathode voltage (three to four KV) would be a

would be a sufficiently noisy supply. The solid-state device could be a Gunn, IMPATT, or avalanche diode driven by about 12-volts DC plus 10-MHz noise. The klystron method is recommended at this time because the relatively high conversion efficiency (15%) would permit a two-watt output with only 15 to 20 watts of driving power. The conversion efficiency of the solid-state devices should soon equal (or perhaps already has equalled) the efficiency of the klystron.

An alternate, FM-by-noise transmitter could be constructed by injecting the output of a Gunn diode, varactor-modulated by noise, into a high-power IMPATT diode oscillator by means of a circulator [15].

The reference signal for the receiver could be obtained by coupling out a sample of the transmitted signal through an "adaptive" attenuator. The attenuator could consist of P-I-N diodes acting as a linear resistor, controlled by an AGC loop in the receiver [14].

The portion of the receiver on the mast (or tower) could consist of the receiving antenna followed by a summing junction for the received and reference signals. The summed signals could then be inserted into a 12-db-gain, two-stage tunnel-diode amplifier [14]. The amplified sum signal would then be led via coaxial cable to the pilothouse (or ground level).

Saturation of the tunnel-diode preamplifier could occur for targets at close range. Correction of this problem would involve either reducing the transmitted power or attenuating the received signal before preamplification. AGC voltage information could be used to lower the power output of the klystron by reducing the beam voltage, or to reduce the input power level to the preamplifier using the P-I-N diode method described above.

Pilothouse (or ground-level) subsystems could consist of the two spectrum analyzers, resulting in the "A" scope display. If the sensitivity of the first spectrum analyzer was poorer than -70 dbm, additional preamplification would probably be necessary. As an alternative approach, the second spectrum analyzer could be replaced by a frequency discriminator to demodulate the video signal of the first spectrum analyzer [4]. The demodulated video signal could then be converted to range information by scaling circuits.

In a scanning system, a conversion to a PPI display could be done by providing appropriate synchronization and antenna reference position signals, along with the video signal from the second spectrum analyzer, to standard PPI display units.

For the small-craft installation, the vertical beamwidth of the antennas should be made large enough to allow for the expected pitch and roll [8]. Scanning and stabilization could be accomplished by standard techniques used for existing small-craft radar systems.

VI. CONCLUSION

The radar system proposed would be useful on small craft for more accurate determination of ranges than is available in current systems, from 30 meters or less to the radar horizon.

VII. RECOMMENDATIONS FOR FURTHER EXPERIMENTS

The existing laboratory equipment could be used for the following experiments:

(1) Refinement of range accuracy by eliminating internal path-length differences for the reference and received signals;

(2) Development of a suitable "A" scope presentation using an FM demodulator followed by frequency-to-range conversion circuits and display;

(3) Conduct of jamming experiments, including use of the system as an active jammer while simultaneously continuing to determine target ranges;

(4) Conversion to single-antenna operation using the increased isolation provided by multiple circulators;

(5) Conversion to a pulsed CW mode of transmission so that the system provides range information only so fast as desired for a particular application; and,

(6) Determination of bearings to targets using two or more receiving antennas and amplitude-comparison techniques [16,17,18].

The increased portability of the solid-state implementation would allow the following to be done, in addition to the above:

(1) Extension of range by increased power together with circuits to recognize the doppler-caused ambiguities that occur at the longer ranges;

(2) Ranging and doppler extraction [5] in a sea-surface-clutter environment; and,

(3) Conversion to a semi-secure communication system wherein two channels of noise from the same source are transmitted, one channel to be modulated with information.

APPENDIX A

BASIC SYSTEM EQUATIONS

Equations used in this paper and developed in Reference 4 are are listed below:

1. Transmitted signal, Fourier transform

A-(1)

$$\phi^{+}(f) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{f_o - f}{\sigma}\right)^2\right)$$

where σ = standard deviation of the noise modulation

f_o = mean transmitted frequency

2. Received signal, Fourier transform

A-(2)

$$\phi^{-}(f) = \phi^{+}(f)\left\{1 + \cos\frac{4\pi f R}{c}\right\}$$

where R = range to the target, meters

c = propagation velocity = 3×10^8 meters/sec

3. Sum of transmitted and received signal after double spectrum analysis

A-(3)

$$\Phi^{-}(t) = \frac{k}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2} S_s^2 \left(\frac{t_o - t}{\sigma}\right)^2\right] \cos\frac{4\pi R S_s t}{c}$$

where S_s = sweep speed of first spectrum analyzer, Hz/sec

4. Range as determined from one spectrum analysis

A-(4)

$$R = \frac{c}{2\,\Delta f_m}$$

where Δf_m = frequency difference between successive nulls.

5. <u>Range as determined from two spectrum analyses</u>

A-(5)
$$R = \frac{c f_m'}{2 S_s}$$

where f_m' = frequency component shown on the second spectrum analyzer.

6. <u>Range resolution</u>

A-(6)
$$\Delta R = \frac{c}{2\pi\sigma}$$

7. <u>Maximum range due to receiver IF bandwidth limitation</u>

A-(7)
$$R_{max} = \frac{c}{20\Delta f_a}$$

where Δf_a = effective IF bandwidth of the first spectrum analyzer.

8. <u>Minimum range due to coherency and transmitted bandwidth limitation</u>

A-(8)
$$R_{min} = l_c = \frac{c}{\Delta f}$$

where l_c = coherence length of the radiation

Δf = transmitted signal bandwidth.

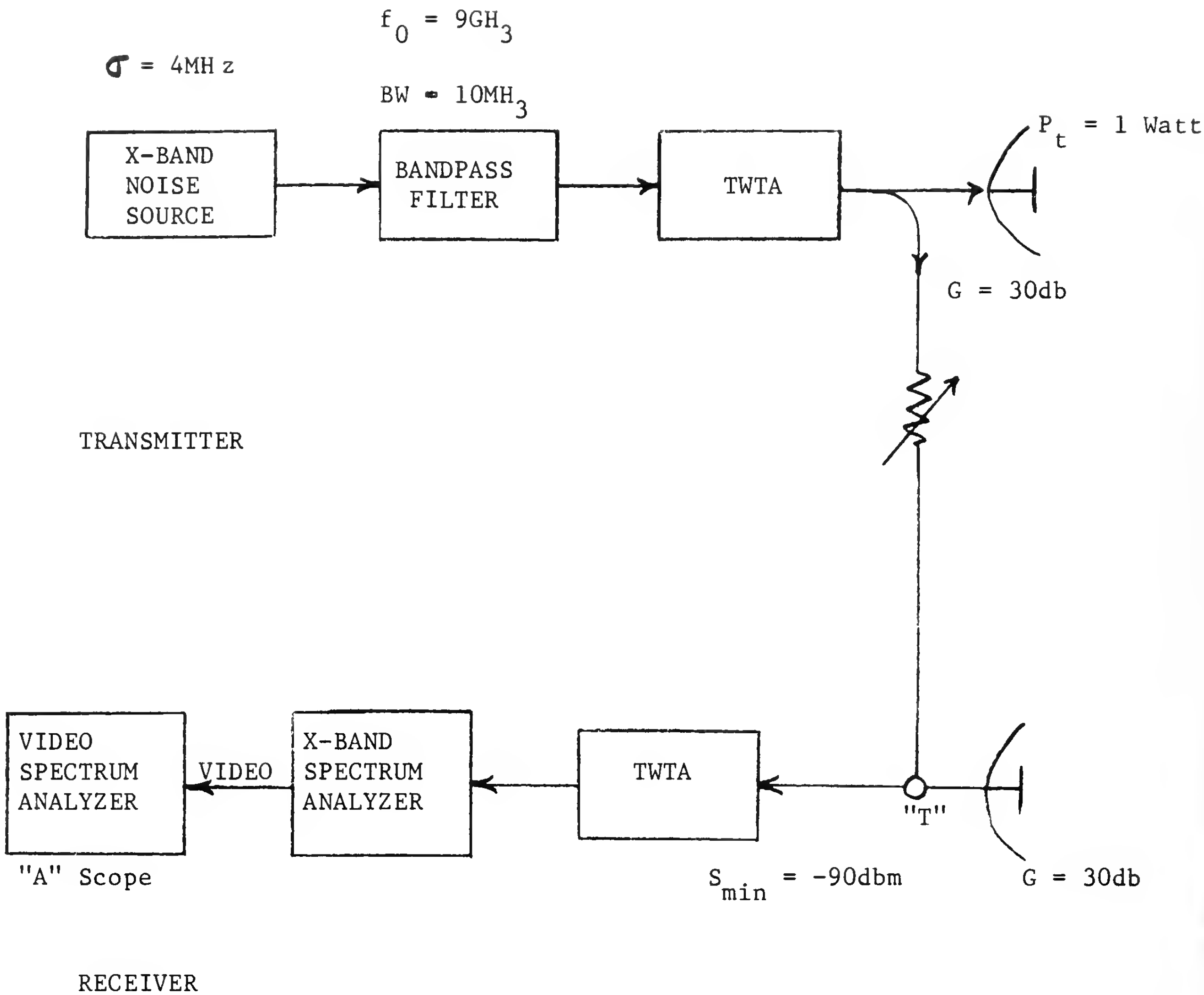


Figure 1 Radar System Model

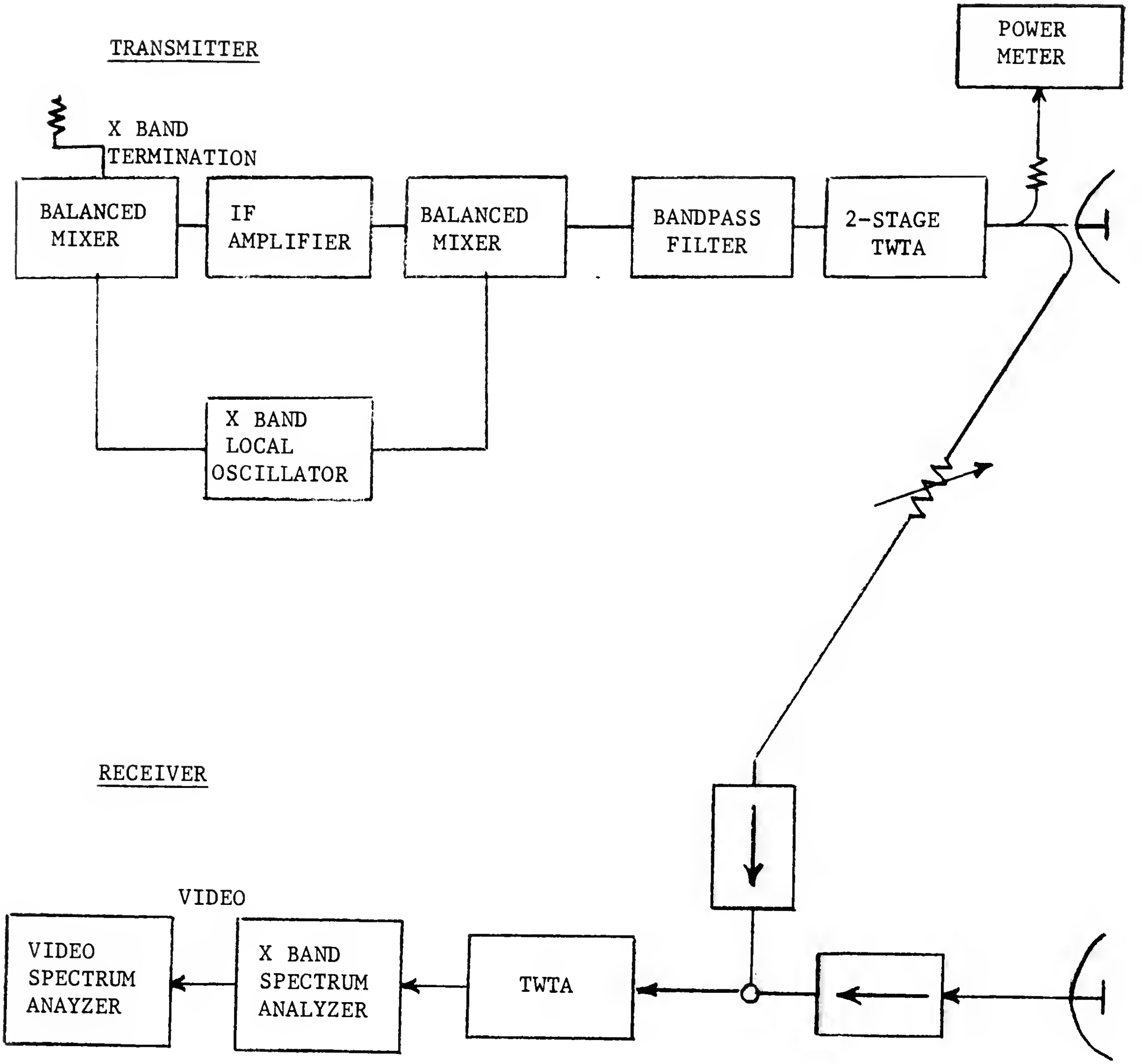
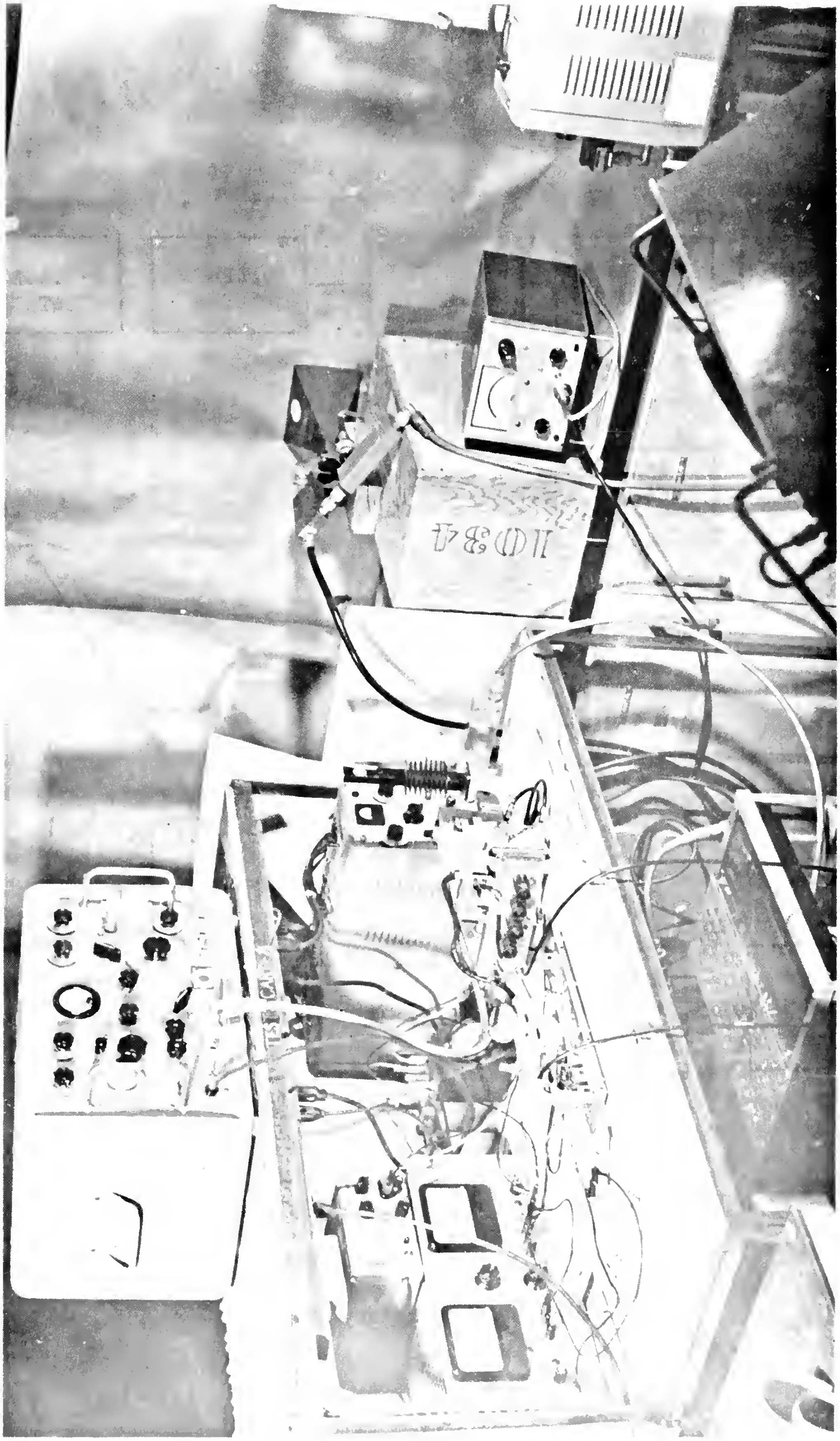


Figure 2 Laboratory System



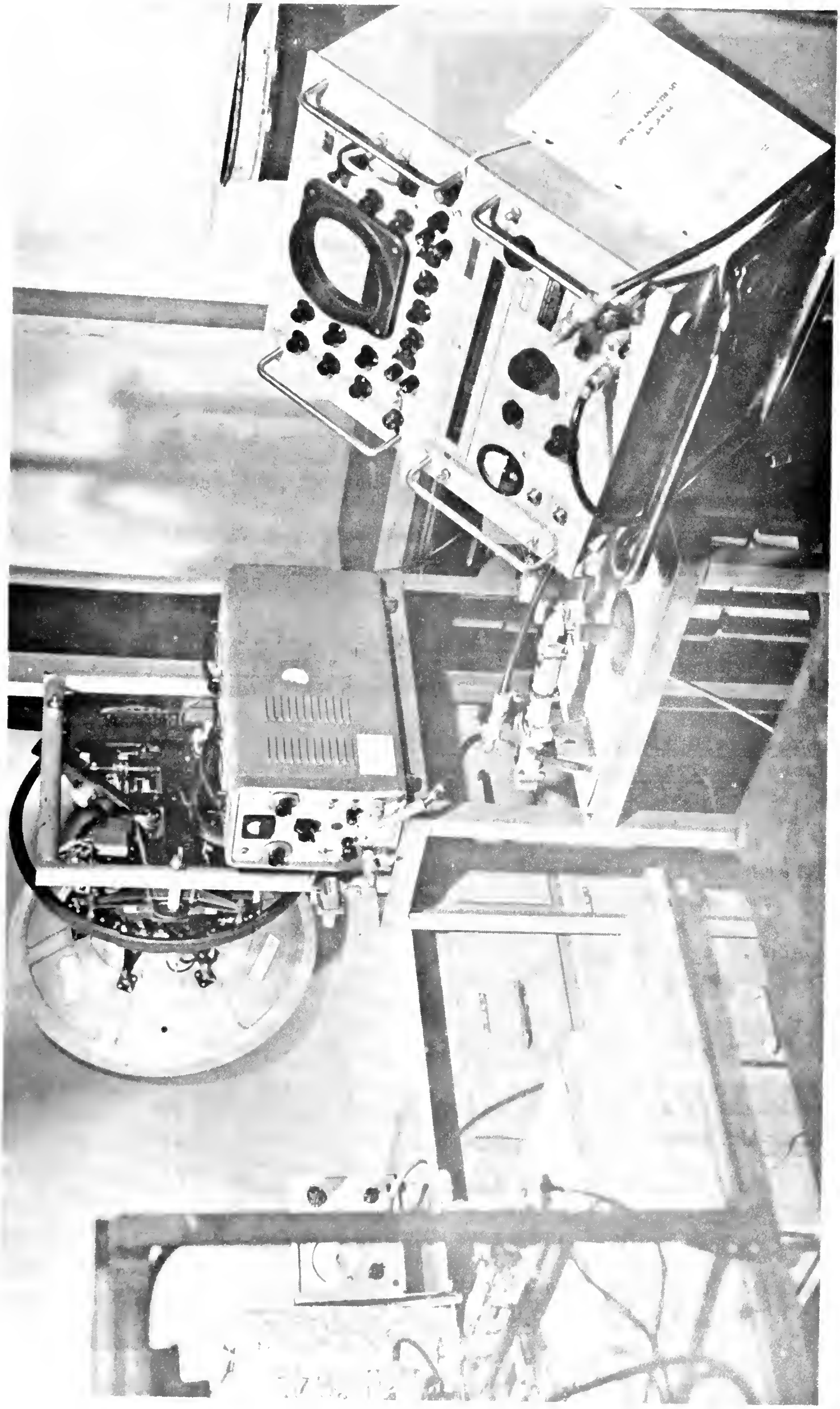


FIGURE 5.

TRANSMITTED AND RECEIVED SIGNALS

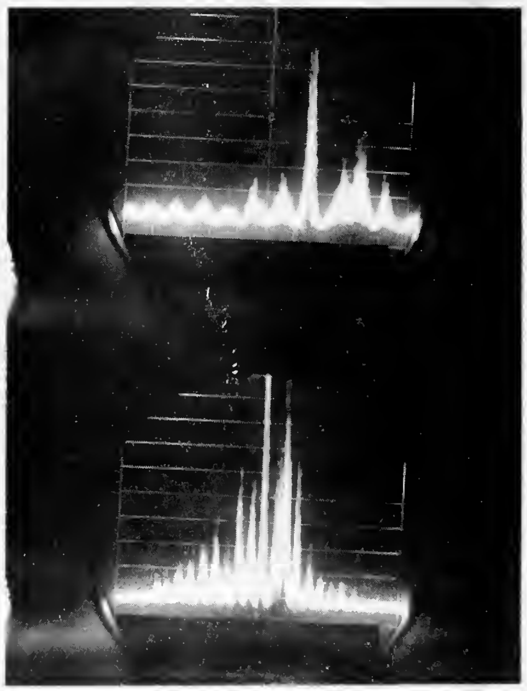


FIGURE 6.

SUM SIGNALS AS VIEWED ON THE FIRST SPECTRUM ANALYZER (TWO SCALES ARE SHOWN)

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13. ABSTRACT

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